AN INVESTIGATION OF THE AMPLIFICATION OF FREQUENCY MODULATED MICROWAVE SIGNALS BY INJECTION LOCKED GUNN-EFFECT OSCILLATORS

by

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THESIS

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ABSTRACT

Although it has been known for many years that under the proper conditions an oscillator can lock to and follow an external signal of much smaller amplitude, this phenomena has not had widespread usage. The development of negative resistance solid state oscillator diodes, such as the Gunn diode, has brought about renewed interest in the locked oscillator, however.

The locking characteristics of an X-Band Gunn-effect oscillator have been investigated. The theory of injection locking is discussed and the experimental work performed is described. Amplifier performance of 20 db gain with 40 MHz bandwidth and 30 db gain with 13 MHz bandwidth is reported.

The advantages of the locked Gunn-effect oscillator as an amplifier for frequency modulated signals are its minimal power supply requirements, small size, low weight, and simplicity.

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E_o	free running oscillator voltage amplitude
E_L	locking signal voltage amplitude
P_o	oscillator output power
P_L	locking signal power
$G = \frac{P_o}{P_L}$	locking gain
$\omega_o = 2\pi f_o$	free running oscillator frequency
$\omega_L = 2\pi f_L$	locking signal frequency
$\Delta\omega_o = \omega_o - \omega_L$	initial frequency difference
$\Delta_o = (\Delta\omega_o)_{max}$	maximum radian frequency separation for locking
α	instantaneous phase angle between locking signal and oscillator voltage phasors
α_{ss}	steady state phase angle for locked operation
Q	loaded Q of oscillator cavity
η	locking figure of merit
f_m	modulation frequency
m_f	frequency modulation index
$(\Delta f)_o$	offset between f_o and carrier of FM signal
N	noise power
$F(\omega)$	noise power spectral density

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CHAPTER I

INTRODUCTION

This study was conducted to investigate the feasibility of using an injection locked Gunn-effect oscillator as an amplifier for frequency modulated microwave signals. Of primary interest were the gain, bandwidth, and frequency response obtainable with an oscillator configuration suitable for operation within a miniaturized system.

The fact that an oscillator can be synchronized with, and made to follow, an external signal of nearly equal frequency and much smaller amplitude has been known for many years. Numerous devices utilizing this principle have been proposed, but none appears to have had widespread usage, probably because at moderate frequencies more conventional methods were always available at equal or lower cost.

At microwave frequencies, however, the problem is somewhat different, since microwave amplifiers tend to be very expensive, are often inconveniently large, and invariably require high voltage power supplies. The opportunity for profitable application of the principle of injection locking to microwave amplification waited only for the development of suitable oscillators.

When the first Gunn diodes, suitable for use in pulsed operation only, were developed, interest was aroused in injection locking as a means to improve pulse to pulse coherence and reduce the time required for oscillations to build up.[1] The development of CW diodes was then inevitably followed by experimentation with injection locking and speculation that small, inexpensive amplifiers, requiring only low voltage power supplies, could be developed. This work pursues that speculation.

The first work with synchronized oscillators at radio frequencies was done in the years immediately preceding 1920. In that year Eccles and Vincent were granted a British Patent on a narrow band FM and code receiver system utilizing a locked oscillator operating at the carrier frequency. A similar system was developed in Germany by H. G. Moller at about the same time.

In 1935 E. H. Armstrong was granted a U.S. Patent on an FM receiver utilizing a locked oscillator operating at the intermediate frequency. A similar application was proposed by Carnahan and Kalmus[2] in 1944. At about the same time another FM receiver system using an oscillator locked to the fifth subharmonic of the first intermiediate frequency was proposed by Beers.[3]

The theory of oscillator synchronization and related phenomena has been studied at length since 1920 by numerous authors, including Appleton[4], van der Pol[5], Byard and Eccles[6], and Tucker[7], but the most straightforward and useful treatment, which has become a standard reference on the subject, was that of Adler[8] in 1946. A treatment similar to Adler's was also incorporated by Slater into his book "Microwave Electronics"[9], published in 1950.

More recent theoretical work has concentrated on topics such as noise[10,11], frequency response[11,12], and the spectrum of the driven but unlocked oscillator[13].

In recent years much experimental work has been done with negative resistance microwave oscillators in such areas as power summing[14], noise reduction[15], and pulse spectrum improvement[16], all of which are attempts to overcome the well-known deficiencies in solid state oscillator performance. As a result of this work, however, progress toward a simple, inexpensive microwave amplifier has been accelerated.

CHAPTER II

THEORY OF INJECTION LOCKING

I. GENERAL

If a signal which differs slightly in frequency from the free running frequency of an oscillator is injected into the oscillator's output port, it cannot be distinguished from a reflected wave. Such a signal thus represents a change in the impedance seen by the oscillator and will have a tendency to pull the frequency in the same manner that reflections from a reactive load can pull the frequency. If the input power is great enough, this frequency pulling can cause the output signal to be phase locked, or synchronized, with the input.

Although the qualitative aspects of injection locking are easily grasped, quantitative solutions quickly get very complicated mathematically. The equations can be solved relatively easily in the case of an unmodulated locking signal, but the transcendental equations which result in the case of a frequency modulated input normally must be solved by computer in numerical or analog form.

In this chapter the unmodulated case is treated fully and the solutions used to study the case of a step function frequency change. Inferences are drawn about the frequency modulated case from the unmodulated and step response. Finally, the results of several authors' work on the FM case are stated.

II. LOCKING TO AN UNMODULATED SIGNAL

Consider an oscillator with free running frequency ω_o and voltage amplitude E_o perturbed by an input signal of frequency ω_L and amplitude E_L. If the driven oscillator is to follow phase variations of the input without noticeable delay, the decay time of the tuned circuit must be short compared to the period of the difference frequency $\Delta\omega_o = (\omega_o - \omega_L)$. For a simple tuned circuit this restriction is equivalent to the statement: $\frac{\omega_o}{2Q} >> \Delta\omega_o$, where Q is the loaded Q of the tuned circuit.

If the restriction stated above applies, amplitude modulation of the output due to amplitude variations of the input will be determined by the magnitude of the input, relative to the output, and the amplitude limiting nonlinearity of the oscillator. Since operation is in the saturated portion of this characteristic, the output amplitude will vary less than the ratio E_L/E_o. Therefore, assuming a small input signal, $E_L << E_o$, amplitude variations of the output can be neglected.

DERIVATION OF THE PHASE OF THE OUTPUT

The phase of the output signal relative to the input may be derived, subject to the foregoing restrictions, by considering the phasor diagram below. (This derivation closely follows the method originally used by Adler[17].) Let the reference frequency be ω_L. Any phasor at rest therefore represents a frequency ω_L, and the frequency of the output is $\omega = \omega_L + \frac{d\alpha}{dt}$, where α is the phase angle between input and output phasors.

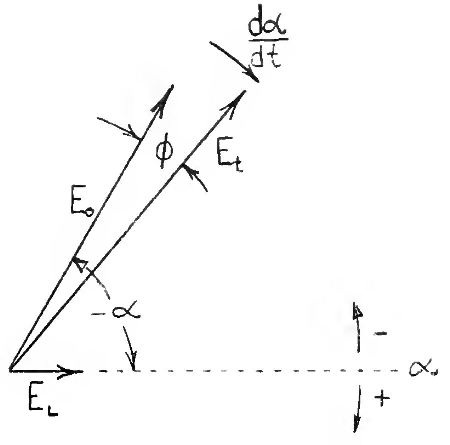

FIGURE 1. PHASOR DIAGRAM

With the assumption that $E_L << E_o$, the resultant oscillator voltage phasor E_t is approximately equal to E_o in magnitude, and the phase shift introduced by the tuned circuit is given by:

$$\phi = \frac{E_L \sin(-\alpha)}{E_o} = -\frac{E_L}{E_o} \sin\alpha \, . \qquad (1)$$

In general for a simple tuned circuit the phase shift introduced at frequencies off resonance is given by:

$\tan\phi = 2Q\frac{\omega-\omega_o}{\omega_o}$; which can be written for small ϕ as:

$$\phi = 2Q\frac{\omega-\omega_o}{\omega_o} \, . \qquad (2)$$

This assumes that operation is confined to the nearly linear portion of the circuit phase characteristic.

The instantaneous frequency difference between input and output is $\Delta\omega = \frac{d\alpha}{dt} = \omega-\omega_L$ and the original or undisturbed frequency difference is $\Delta\omega_o = \omega_o-\omega_L$. Using these quantities equation (2) can be rewritten:

$$\phi = \frac{2Q}{\omega_o}(\Delta\omega - \Delta\omega_o) = \frac{2Q}{\omega_o}\left[\frac{d\alpha}{dt} - \Delta\omega_o\right] \quad . \qquad (3)$$

Substituting equation (1) in equation (3) and solving for $\frac{d\alpha}{dt}$ yields the differential equation for α:

$$\frac{d\alpha}{dt} = \Delta\omega_o - \frac{\omega_o}{2Q}\frac{E_L}{E_o}\sin\alpha \quad . \qquad (4)$$

STEADY STATE SOLUTION

Examination of equation (4) immediately suggests a steady state solution for which the output is fully locked to the input. With $\frac{d\alpha}{dt} = 0$, equation (4) can be solved for the steady state phase angle:

$$\sin\alpha_{ss} = 2Q\frac{E_o}{E_L}\frac{\Delta\omega_o}{\omega_o} \quad ; \qquad (5)$$

and since $|\sin x| \leq 1$, the maximum locking range is given by:

$$\left|2Q\frac{E_o}{E_L}\frac{\Delta\omega_o}{\omega_o}\right| \leq 1 \quad . \qquad (6)$$

Rearranging, and defining $\Delta_o = (\Delta\omega_o)_{max}$:

$$\Delta_o = \frac{\omega_o}{2Q}\frac{E_L}{E_o} \quad . \qquad (7)$$

It is more convenient for use with microwave oscillators to reframe equation (7) in terms of power. A figure of merit for a locked oscillator can be defined as the product of fractional locking bandwidth and voltage gain :

$$\eta = \frac{2\Delta_o}{\omega_o}\frac{E_o}{E_L} \quad . \qquad (8)$$

It can be easily seen that for the voltage gain case, $\eta = \frac{1}{Q}$.

If the power gain is defined as $G = E_o^2 / E_L^2 = P_o / P_L$, any uncertainty in the exact value of the voltage produced by the input power is absorbed in η. Then η will lie between $\frac{1}{Q}$ and $\frac{2}{Q}$, depending on the degree of reflection of the input power at the oscillator port. The figure of merit is then:

$$\eta = \frac{2\Delta_o}{\omega_o} \sqrt{\frac{P_o}{P_L}} \quad ; \qquad (9)$$

and equation (7) becomes:

$$\Delta_o = \eta \frac{\omega_o}{2} \sqrt{\frac{P_L}{P_o}} \quad . \qquad (10)$$

SOLUTION FOR THE PHASE AS A FUNCTION OF TIME

With the substitution $k = \sin \alpha_{ss} = 2Q \frac{E_o}{E_L} \frac{\Delta\omega_o}{\omega_o}$, equation (4) can be rewritten:

$$\frac{d\alpha}{dt} = \Delta\omega_o - \frac{\Delta\omega_o}{k} \sin \alpha \quad . \qquad (11)$$

Separating variables,

$$\int dt = \int \frac{d\alpha}{\Delta\omega_o - \frac{\Delta\omega_o}{k} \sin \alpha} \quad ,$$

integration yields:

$$t - t_o = \frac{2}{\sqrt{(\Delta\omega_o)^2 - \left(\frac{\Delta\omega_o}{k}\right)^2}} \tan^{-1}\left[\frac{\Delta\omega_o \tan\frac{\alpha}{2} - \frac{\Delta\omega_o}{k}}{\sqrt{(\Delta\omega_o)^2 - \left(\frac{\Delta\omega_o}{k}\right)^2}}\right] \quad ;$$

where t_o is an integration constant. Rearranging and solving for α, with $\Delta_o = \frac{\Delta\omega_o}{k}$:

$$\alpha = 2\tan^{-1}\left[\frac{1}{k} + \frac{\sqrt{k^2 - 1}}{k}\tan\frac{\Delta_o(t - t_o)}{2}\sqrt{k^2 - 1}\right]. \quad (12)$$

For operation within the locking range $|k| < 1$ and $\sqrt{k^2 - 1} = j\sqrt{1 - k^2}$. With the application of the identity $j\tan(jx) = -\tanh x$ the solution becomes:

$$\alpha = 2\tan^{-1}\left[\frac{1}{k} - \frac{\sqrt{1 - k^2}}{k}\tanh\frac{\Delta_o(t - t_o)}{2}\sqrt{1 - k^2}\right]. \quad (13)$$

Since tanh x goes monotonically to one as x approaches infinity, a steady state is indeed reached, and with $k = \sin\alpha_{ss}$:

$$\frac{1 - \sqrt{1 - k^2}}{k} = \frac{1 - \cos\alpha_{ss}}{\sin\alpha_{ss}} = \tan\frac{\alpha_{ss}}{2}$$

by trigonometric identity, thus confirming the steady state solution, equation (5).

THE UNLOCKED DRIVEN OSCILLATOR

Equation (12) gives the phase angle as a function of time for an unlocked driven oscillator, but does not permit easy visualization of the output under these conditions. Another approach, due to Stover[18], yields more useful information about the output spectrum of the unlocked driven oscillator.

Assume the driven oscillator output voltage is:

$$e = E_o \sin[\omega_L t - \alpha(t)] \quad ; (14)$$

where the restriction $E_L \ll E_o$ permits the use of E_o. The free running frequency is ω_o and the driver frequency is ω_L.

Using equation (11) again:

$$\frac{d\alpha}{dt} = \Delta\omega_o - \frac{\Delta\omega_o}{k} \sin \alpha \quad ; \qquad (11)$$

making the transformation:

$$\frac{d\alpha}{dt} = \Delta\omega_o - \frac{d\varepsilon}{dt} \quad ;$$

and substituting the parameters $\Omega = \Delta\omega_o$, $\tau = \Omega t = (\Delta\omega_o)t$, and $k = \frac{\Delta\omega_o}{\Delta_o}$,

allows the differential equation for $\varepsilon(\tau)$ to be written:

$$\frac{d\varepsilon}{d\tau} = \frac{1}{k} \sin [\tau - \varepsilon(\tau)] \quad . \qquad (16)$$

Expansion of $\varepsilon(\tau)$ in powers of $\frac{1}{k}$ and substitution in equation (16) with terms in $\frac{1}{k}$ retained to third order yields:

$$\varepsilon(\tau) = \frac{1}{k}\left\{(1 + \frac{\tau}{2k} + \frac{1}{6k^2}) - (1 + \frac{1}{4k^2}) \cos [\tau - \beta(\tau)] + \frac{1}{4k} \sin [2(\tau - \beta(\tau))] + \frac{1}{12k^2} \cos[3(\tau - \beta(\tau))] + \ldots\right\}; \qquad (17)$$

where $\dot{\beta}(\tau) = \frac{1}{2k^2\Delta_o}$.

Substitution of this expression in equation (14) gives for the output voltage:

$$e = E_o\left\{(1 - \frac{1}{4k^2}) \sin (\omega't + \Psi_c) - \frac{1}{2k} (1 + \frac{1}{4k^2})\cos[\omega't+(\Omega t-\beta(t))+\gamma_{1+}] - \frac{1}{2k} \cos [\omega't-(\Omega t-\beta(t))+\gamma_{1-}] - \frac{1}{4k^2} \sin [\omega't-2(\Omega t-\beta(t))+\gamma_2] + \frac{1}{8k^3} \cos [\omega't-3(\Omega t-\beta(t))]\right\} \quad ; \qquad (18)$$

where the phase angles Ψ_c, γ_{1+}, γ_{1-}, and γ_2 are factors of $\frac{1}{k}$ and $\left(\frac{1}{k}\right)^3$.

Inspection of equation (18) indicates the following important features of the spectrum.

(1) The carrier is shifted in frequency from ω_o to $\omega' = \omega_o + \frac{\Delta\omega_o}{2k^2}$.

(2) The carrier amplitude decreases as k is decreased and the amount of frequency shift increases.

(3) There are two first order sidebands of unequal amplitude, one of which is at the driving frequency, $\omega_L = \omega' + (\Omega - \dot{\beta})$. This sideband's amplitude increases more rapidly than that of the other as k is decreased.

(4) Second and higher order sidebands appear only on the side of the spectrum opposite the driver. Absence of fourth and higher order sidebands can be attributed to the termination of the power series expression for $\varepsilon(\tau)$ after third order terms.

(5) The ratio of the amplitudes of adjacent sidebands, E_{n+1} / E_n , is equal to 2k, and thus Δ_o can be estimated from the unlocked spectrum.

III. LOCKING TO A FREQUENCY MODULATED SIGNAL

RESPONSE TO A FREQUENCY STEP FUNCTION

Assume a locked oscillator is operating with the free running frequency equal to the locking frequency. In this situation the initial steady state phase angle is zero and $k_o = 0$. If an ideal frequency step function is applied, the effect in equation (13) is that of a step change in k from zero to k_1 at time t = 0. Under these conditions equation (13) becomes, for $t > 0$:

$$\alpha(t) = 2 \tan^{-1}\left[\frac{1}{k_1} - \frac{\sqrt{1 - k_1^2}}{k_1} \tanh \frac{\Delta_o t}{2}\sqrt{1 - k_1^2}\right] \quad ; \tag{19}$$

assuming the step frequency change is less than the maximum locking range Δ_o.

Since tanh x goes monotonically to one with increasing x, the steady state will be reached when $\tanh \frac{\Delta_o t}{2} \sqrt{1 - k_1^2} \simeq 1$. Noting that tanh 3 = .995, it is seen that the steady state is essentially reached at time T given by:

$$T = \frac{6}{\Delta_o \sqrt{1 - k_1^2}} \quad . \tag{20}$$

With the substitution of equation (10) for Δ_o, equation (20) becomes:

$$T = \frac{6}{\Pi \sqrt{1 - k_1^2}} \quad \frac{1}{\eta f_o} \sqrt{\frac{P_o}{P_L}} \quad . \tag{21}$$

The difference between instantaneous and steady state phase angles is plotted as a function of time for four values of k_1 in Figure (2). These curves confirm that locking is essentially complete for

$$t = \frac{6}{\Delta_o \sqrt{1 - k_1^2}} \quad .$$

RESPONSE TO A SINUSOIDALLY MODULATED FM SIGNAL

Although an exact solution for the case of a sinusoidally modulated input would be extremely difficult, it is possible to estimate an approximate upper limit on modulating frequency using the step response data above.

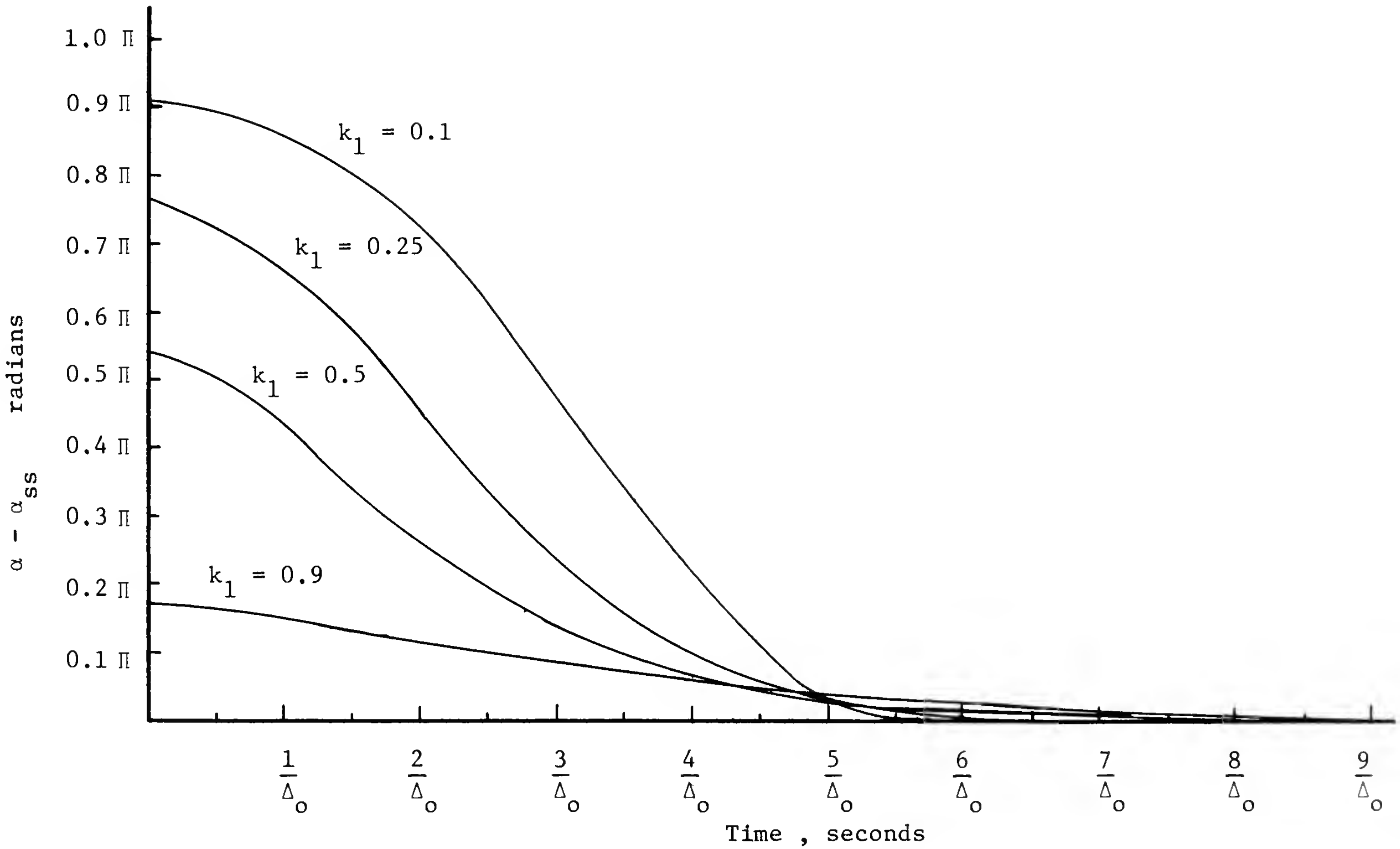

FIGURE 2. TRANSIENT PHASE RESPONSE TO A FREQUENCY STEP FUNCTION

Under sinusoidal modulation conditions the time T derived above roughly corresponds to half a modulation cycle at the highest modulating frequency possible without distortion. Thus a nominal upper modulating frequency limit is given by:

$$\omega_{max} = \frac{\Delta_o \sqrt{1 - k^2}}{12} \quad ; \qquad (22)$$

or:

$$f_{max} = \frac{\pi\sqrt{1 - k^2}\ \Delta_o}{6} = \frac{\pi \sqrt{1 - k^2}\ \eta f_o}{12} \sqrt{\frac{P_L}{P_o}} \quad ; \qquad (23)$$

where k is that value corresponding to the maximum frequency deviation of the input. For example, if f_o = 10 GHz, G = 20 db, η = 0.04, ($2\pi\Delta_o$ = 20 MHz), and k = 0.707 : f_{max} = 7.4 MHz.

Since the phase angle given by equation (19) is never larger than π radians, it is easily seen that sinusoidal variations in the input frequency at a higher rate than f_{max} will be followed, but the full frequency deviation of the input will not be reached. This effect becomes more pronounced as the modulation frequency is increased.

The preceding conclusion is supported by the results of a study by Isobe and Tokida[19] in which the equivalent of equation (11) was solved for the FM case by analog computer. This solution indicates that f_{max} as calculated above represents the frequency at which approximately 90% of the input frequency deviation is reproduced by the oscillator. For a modulating frequency of 2 f_{max} approximately 78% of the input deviation is reproduced.

Stover and Shaw[20] have derived an expression for the frequency response of the locked oscillator in terms of the relative gain for the sidebands of an FM signal. Their result for low index FM sidebands at $\omega_L \pm \omega_i$ is:

$$\frac{P_{i\ out}}{P_{i\ in(FM)}} = \frac{G}{1 + \left(\frac{\omega_i}{\Delta_o \cos \alpha_{ss}}\right)^2} \quad ; \qquad (23)$$

where $G = \sqrt{\frac{P_o}{P_L}}$. The locked oscillator can therefore be represented as a linear amplifier followed by a first order Butterworth filter.

NOISE CHARACTERISTICS

Several authors have studied the problem of noise in locked oscillators, both from the standpoint of noise figures in amplifier applications and from the standpoint of noise reduction by locking to a less noisy source. Although no experimental work was done by this author on noise characteristics, some of the results found by others are included in the interests of completeness.

Stover and Shaw[21] give for the noise contribution of a locked oscillator used as an FM amplifier:

$$\frac{N_{out/cycle}}{N_{in/cycle}} = \frac{1}{2}(1 + \tan^2 \alpha_{ss}) \frac{G}{1 + \left(\frac{\omega_i}{\Delta_o \cos \alpha_{ss}}\right)^2} \quad ; \qquad (24)$$

where AM to FM noise conversion varies as $\tan^2 \alpha_{ss}$. It is therefore evident that the conversion of AM noise to FM noise does not occur if $\alpha_{ss} \simeq 0$, that is, for $\omega_L \simeq \omega_o$. Under these conditions the equivalent block diagram in Figure (3) applies[22].

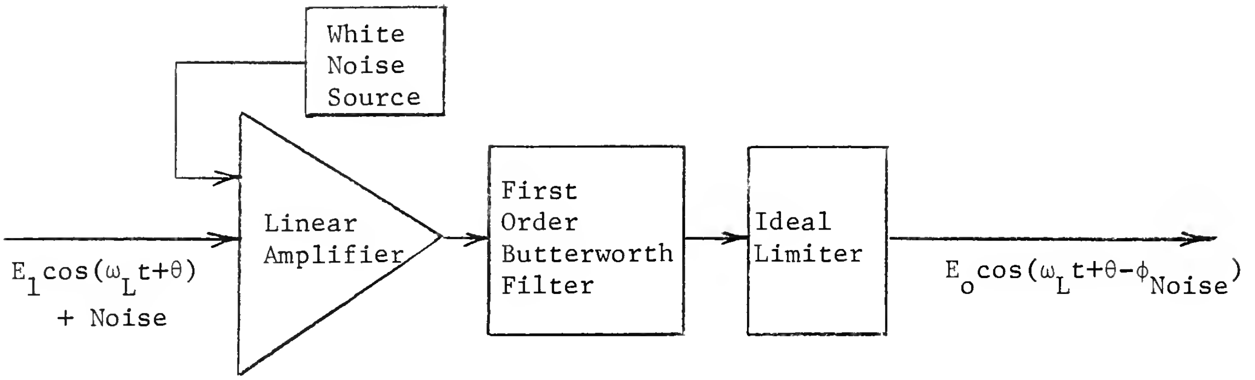

FIGURE 3. EQUIVALENT BLOCK DIAGRAM OF LOCKED OSCILLATOR

A more general expression developed by Kurakawa[23] for the resultant noise power spectral density $F(\omega)$ of an oscillator having noise spectral density $F_o(\omega)$, locked to a source with noise spectral density $F_1(\omega)$ is, in the notation used here:

$$F(\omega) = \frac{1 - k^2}{1 - k^2 + \left(\frac{\omega}{\Delta_o}\right)^2} F_1(\omega) + \frac{\left(\frac{\omega}{\Delta_o}\right)^2}{1 - k^2 + \left(\frac{\omega}{\Delta_o}\right)^2} F_o(\omega) \quad . \qquad (25)$$

Experimental verification of this expression has been provided by Sugiura and Sugimoto[24].

CHAPTER III

EQUIPMENT AND EXPERIMENTAL TECHNIQUES

I. GENERAL

Included in this chapter are details of the experimental equipment and procedures used in studying the injection locked Gunn-effect oscillator. Restrictions imposed by time and budget limited the equipment almost entirely to that which was currently available at the Postgraduate School or that which could be constructed. Important exceptions to this general statement were the Gunn diodes, graciously provided by Varian Associates, without which there would have been no experimental work.

With the exception of the oscillator cavities, which were constructed, standard laboratory instruments, signal sources, and waveguide circuit components were used throughout the experimental work.

II. EQUIPMENT

GUNN DIODES

Two Varian VSX-9205A CW Gunn diodes were obtained from Varian Associates, Palo Alto, California. The diode characteristics are listed in Table I below.

TABLE I. GUNN DIODE CHARACTERISTICS

Serial number	7A	8A
Operating voltage	9.0 volts	9.0 volts
Operating current	0.33 amp	0.22 amp
Threshold voltage	4.2 volts	4.1 volts
Threshold current	0.41 amp	0.32 amp
Maximum output power . .	29 mW	37 mW
Maximum power frequency .	10.5 GHz	10.0 GHz

RESONANT CAVITIES

Several considerations led to the choice of a coaxial cavity for the oscillator resonant circuit. These included provision for mounting the diode and adjusting its position within the cavity, application of the d.c. bias, and wide range mechanical tuning.

Placement of the diode in the center conductor of the coaxial cavity permitted efficient coupling to the cavity mode, and diode location was easily adjustable by moving the entire center conductor. This also permitted convenient application of the d.c. bias by insulation of one end of the cavity and one portion of the center conductor from the remainder of the cavity.

Since it was intended to investigate operation throughout X-Band, a wide range of mechanical tuning, without secondary effects such as changes in mode structure, was desired. This was provided by the coaxial cavity with moveable shorting piston. The length of the cavity was such that operation was possible in 1/2, 1, or 1 1/2 wavelength TEM modes throughout X-Band. The inner and outer conductor radii were chosen to insure that waveguide modes were below cutoff throughout the desired frequency range. The mechanical details of the tunable coaxial cavity are shown in Figure (4). The material used in the construction of this cavity was aluminum,

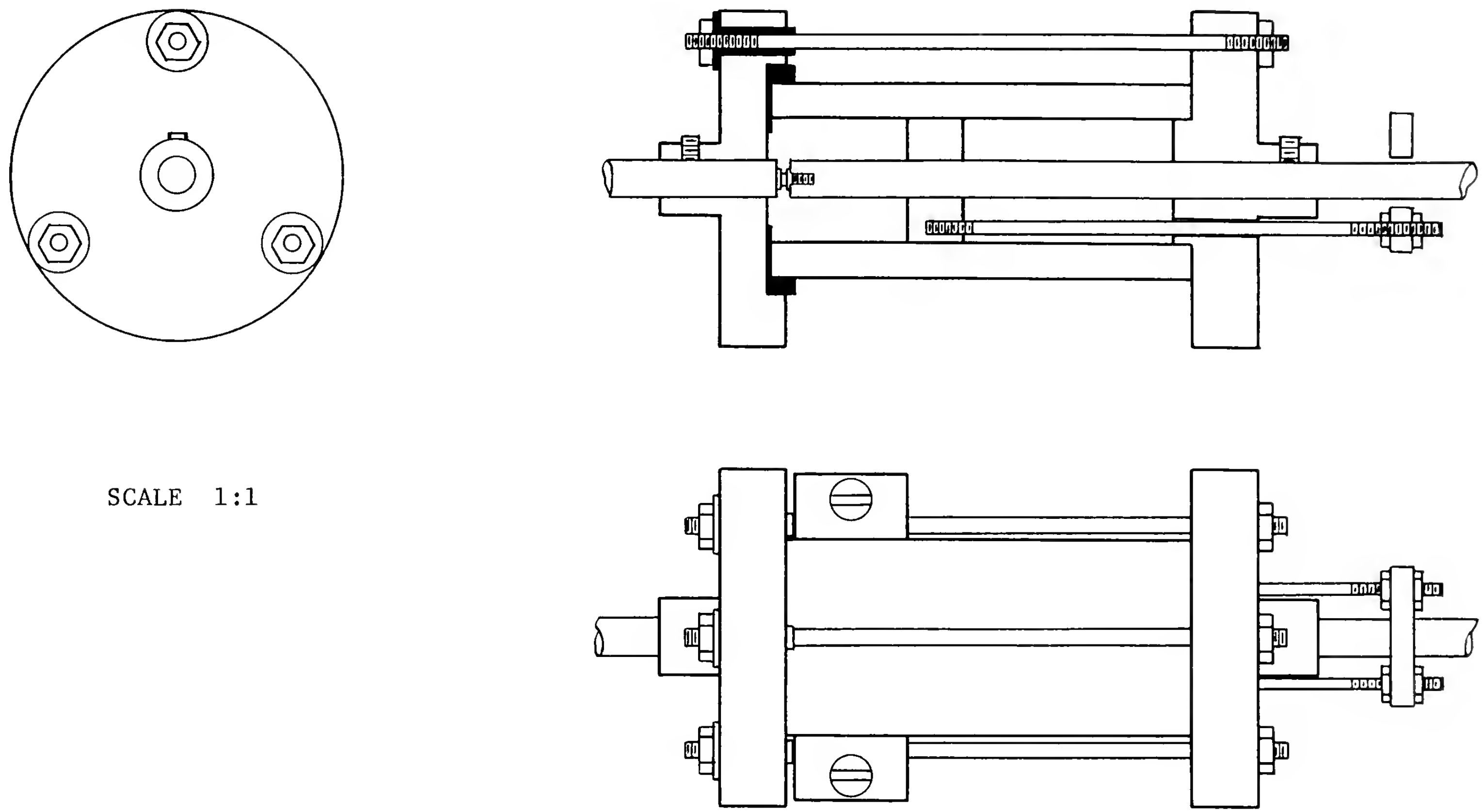

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FIGURE 4. TUNABLE COAXIAL CAVITY

except for the center conductor, which was brass.

Several problems were encountered with this cavity design. Losses in the brass center conductor proved to be excessive, but copper plating eliminated this problem. Wear on the contacting surfaces of the outer conductor and the sliding short caused the tuning and power output to become very erratic after the cavity had been in use for some time. The short was replaced with another which fitted tightly, but this was only a temporary solution. After sufficient data was gathered about operation at frequencies throughout X-Band another cavity of similar design, but with no provision for tuning, was constructed. Outer conductors of 3 different lengths were made, however, to allow operation at 8.9, 10.0, or 12.0 GHz, and use of a shim with each of the outer conductors also allowed operation at 8.3, 9.4, or 11.0 GHz. As Figure (5) shows, the design was quite similar to the previous cavity with the exception of tuning provisions. The materials used were copper or copper-plated brass throughout.

Another problem was coupling the cavity to the load. As seen in equation (6), the locking bandwidth at a given gain is inversely proportional to the loaded Q of the cavity. With the coaxial coupling used, the lowest loaded Q obtainable before output power began to be adversely affected was about 25. It would have been desirable to reduce this figure to about 10, but this was not possible with loop or probe coupling. A cavity directly coupled to a waveguide would have provided a lower loaded Q, but in many applications, such as use with a stripline circuit, the coaxial input would be desirable. The value of 25 may represent the lowest loaded Q obtainable in such an application.

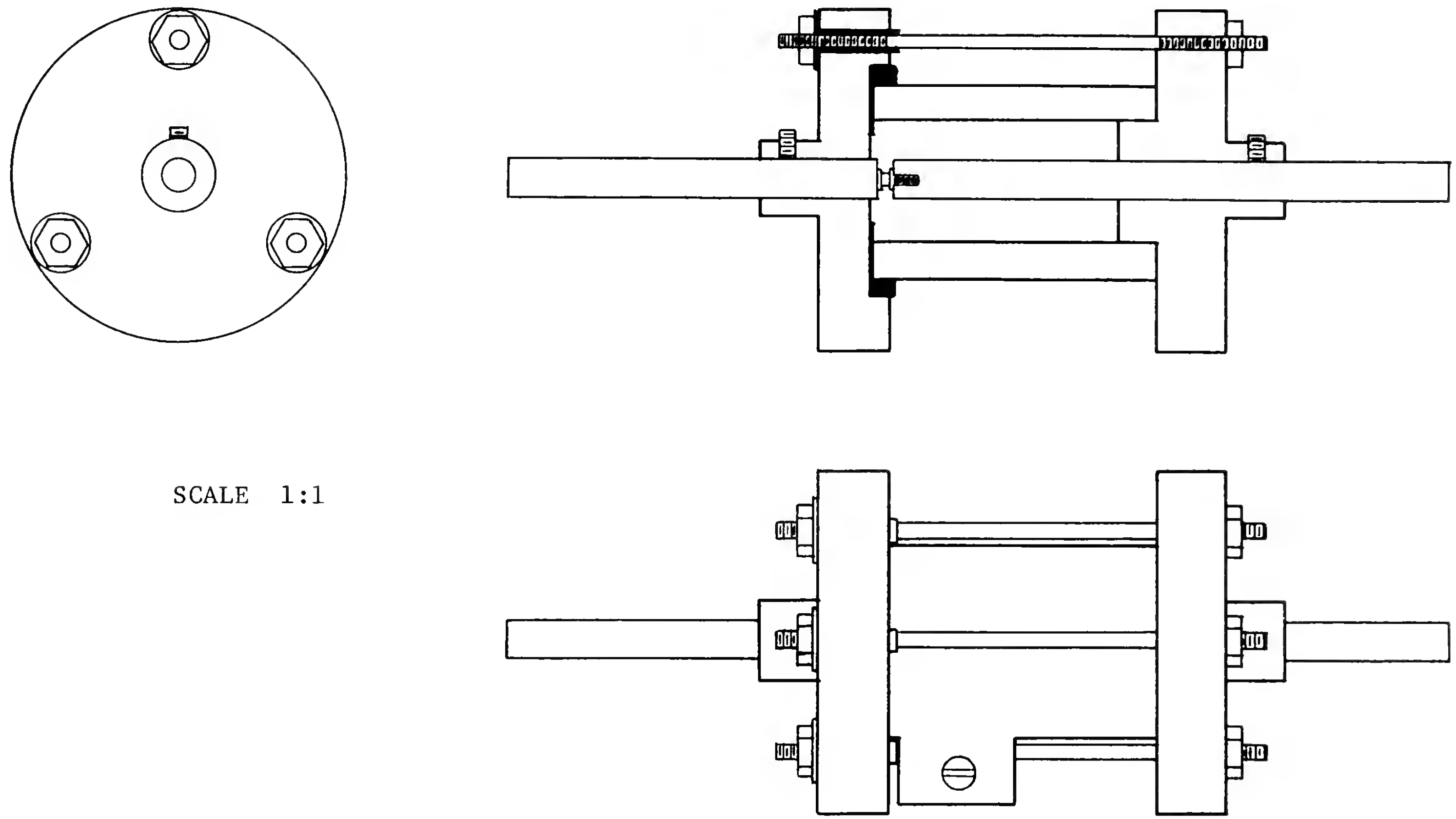

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FIGURE 5. FIXED TUNED COAXIAL CAVITY

MICROWAVE CIRCUITS

Two microwave circuits were used in the course of experimental work. Both were composed strictly of standard laboratory waveguide components. The first, used during optimization of diode location and initial power measurements, is shown in Figure (6). This circuit was used only until the output power obtained was near rated values.

The second circuit was used for the remainder of the experimental work, including CW and FM locking experiments. It consisted of basically the same circuit as #1 with a circulator and provision for locking source incorporated. This circuit is shown in Figure (7).

The instruments used were: Polarad SA-84W Spectrum Analyzer, Hewlett-Packard 431B Power Meters, and a Tektronix 515A Oscilloscope. Signal sources were a Varian Reflex Klystron with Hewlett-Packard 715A power supply or an Alfred Model 605 BWO Sweep Oscillator. For frequency modulation experiments the Sweep Oscillator was externally modulated using a General Radio Bridge Oscillator.

II. EXPERIMENTAL TECHNIQUES

CALIBRATION

Circuit #2 was calibrated throughout the frequency range of interest. This included comparison of the input power measured at the directional coupler with that measured at the cavity input, and a similar comparison of output power at the cavity with that measured at the directional coupler on the output line. In this

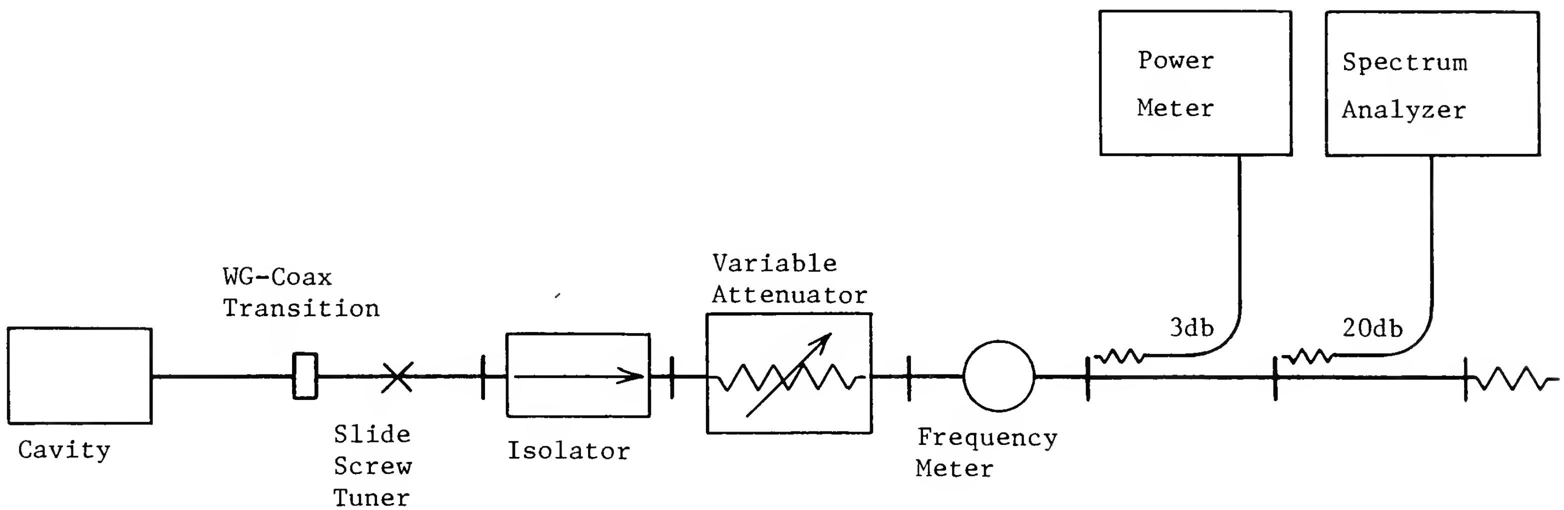

FIGURE 6. MICROWAVE CIRCUIT #1

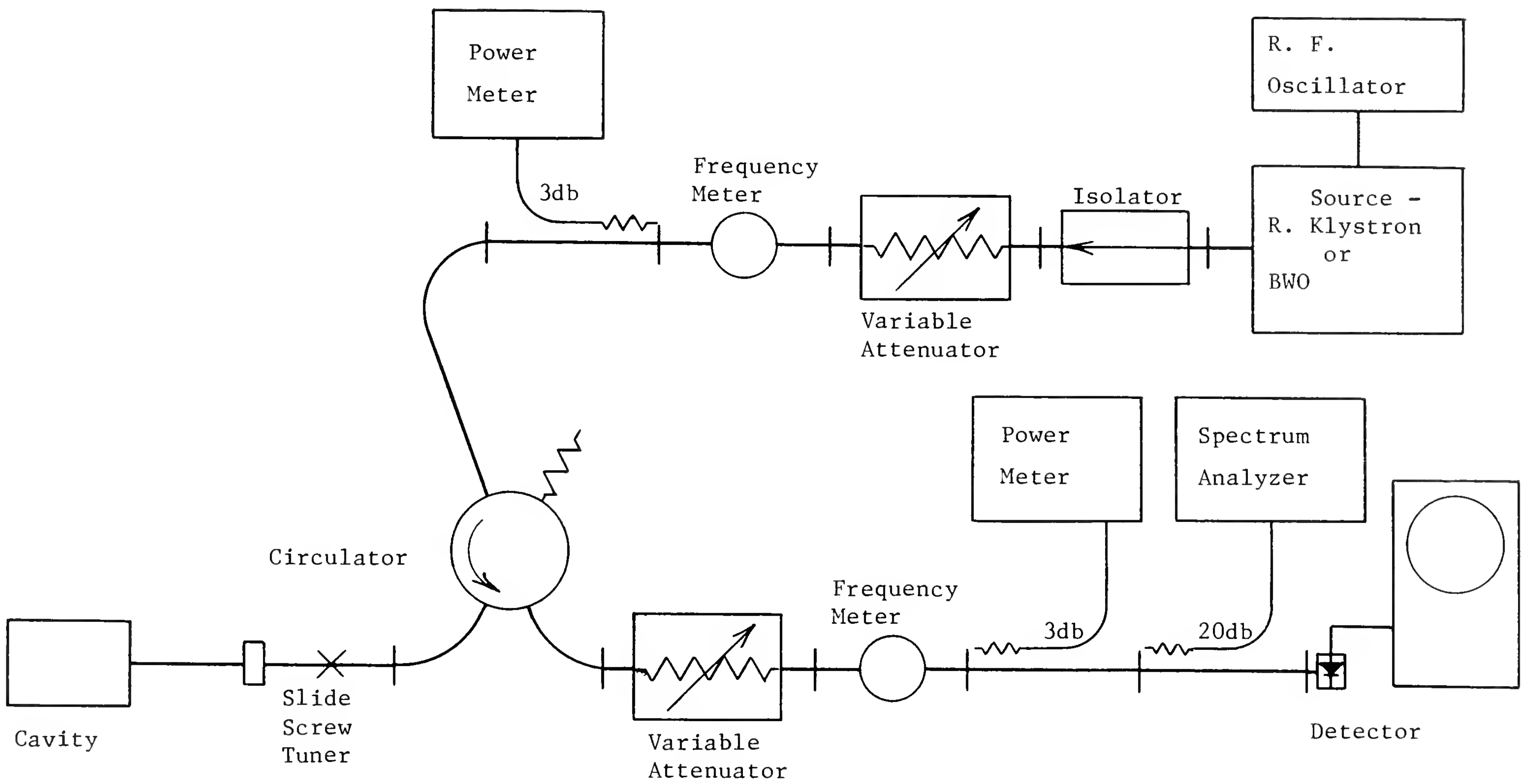

FIGURE 7. MICROWAVE CIRCUIT #2

way all losses were accounted for, and any uncertainty about the exact value of the directional coupler parameters was eliminated.

Calibration measurements showed that circulator performance deteriorated seriously above 10.5 GHz, therefore locking measurements were made only at frequencies of 10 GHz and below.

The coaxial input line to the cavity was also calibrated at frequencies up to 10.5 GHz. It was found to have fairly constant, though considerable, attenuation over the frequency range from 8.5 to 10.5 GHz.

Power meters were cross compared to insure tracking and were found to be well calibrated. The frequency meters were also compared with each other and with the spectrum analyzer frequency difference scale. The frequency meters tracked well, but there was a 4 MHz constant offset between their readings. The meter in the output line was chosen as a reference since CW locking range was measured using this meter alone. The spectrum analyzer frequency deviation scale proved to be quite inaccurate over some portions of its range. It was therefore not used in measuring frequency deviations during locking experiments.

MEASUREMENTS

During the first phase of the experimental work output power was measured at frequencies throughout X-Band. Output was also noted during all locking experiments.

Locking gains and bandwidths for CW inputs were measured in three different ways. The first was to set a given frequency deviation and increase input power until locking was observed on the spectrum analyzer. The frequencies in the free running and locked states were measured by observing the dip in detected output on the oscilloscope as the frequency meter was tuned to the operating frequency. This method proved to be quite satisfactory.

The second and third methods used in CW locking measurements were very similar. In both cases the gain was set at a fixed level and the frequency of the input varied. The BWO was the only source used in these measurements. In one case it was electronically swept and in the other case the frequency was manually varied. Output power variations of the BWO over even relatively small frequency ranges made both of these methods undesirable.

Similar procedures were used to measure locking gains for frequency modulated inputs. The first method was to set a fixed gain and increase the frequency deviation of the input until lock was broken. The second method was to set a fixed input frequency deviation at low gain and reduce the input until lock was broken or significant reduction in deviation occurred, for example disappearance of the highest order sidebands. These procedures yielded almost identical results, but the first was normally used for convenience.

Voltage tuning effects were also investigated by varying the d.c. bias and observing the resultant variation in output power and frequency.

CHAPTER IV

EXPERIMENTAL RESULTS

I. GENERAL

The results of experimental work performed are presented in this chapter. Included are details of experiments to determine mechanical and voltage tunability of the Gunn-effect oscillator, locking performance with unmodulated and frequency modulated locking signals, and other details such as the effect of amplitude modulation on locking performance.

The results for unmodulated locking signals were found to be in close agreement with the theory presented in Chapter II. The gain-bandwidth products obtained for frequency modulated signals followed theoretical predictions fairly well, but the effect of modulating frequency was much greater than predicted. This was due to the excessive amount of spurious amplitude modulation which resulted when large frequency deviations or high modulating frequencies were used with the locking signal source.

The spectrum of the unlocked driven oscillator was also investigated and compared with theoretical predictions. It was found to agree with theory to within the limits of the assumptions used in the derivation.

II. POWER OUTPUT AND TUNING

MECHANICAL TUNING

Before any other measurements were made it was necessary to find a suitable diode-cavity configuration for the production of useable output power. It was expected that the diode would operate best in a low impedance region of the cavity. It was accordingly located near one end. The degree of sensitivity to location was much greater than anticipated, however, and the first placement of the diode yielded only bias circuit oscillations at about 5 MHz with barely perceptible microwave power.

A filter was added to the bias circuit as suggested in the diode operating instructions. This consisted of a 30 ohm resistor and a 0.068 microfarad capacitor in series across the diode bias as shown in Figure (8). The filter eliminated the bias circuit oscillations, but did not increase microwave power output.

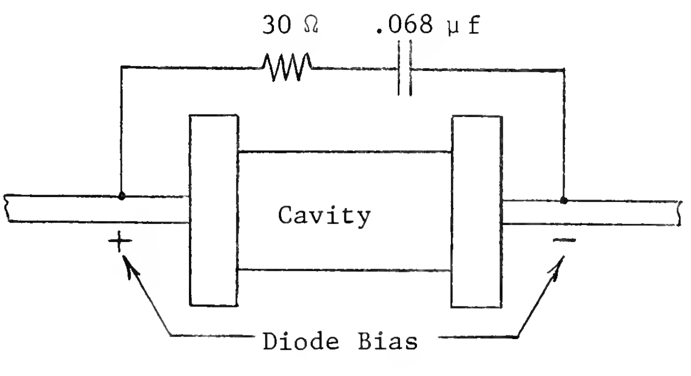

FIGURE 8.
FILTER TO PREVENT BIAS CIRCUIT OSCILLATION

Movement of the diode closer to the end of the cavity produced immediate large increases in power output and with further slight adjustments more than 24 mW output power was obtained. The extreme sensitivity of the diode to impedance is demonstrated by the fact that a total movement of approximately 0.25 cm increased the power output from less than 0.1 mW to 24 mW.

During the course of all measurements power outputs greater than 20 mW were obtained at frequencies from 8.5 to 11.5 GHz. No attempt was made to obtain a true power versus frequency curve because tuning and power output began to be erratic as the contacting surfaces of the cavity became worn through use. Figure (9) displays power outputs which were recorded throughout the course of experimental work, representative of the maximum power output obtainable over the frequency range. These outputs were obtained with diode 7A, which was the only one used in locking experiments.

The short term frequency stability of the Gunn diodes was good -- better than either the Klystron or the BWO. Figure (10) is a photograph of the spectrum at 11.1 GHz. Spectral width is 0.2 MHz, which is the limit of the spectrum analyzer resolution.

VOLTAGE TUNING

Voltage tuning was investigated as a means to make minor adjustments to the operating frequency, for such purposes as fine synchronization of the free running frequency with the locking frequency. It was found that a useful tuning range, 20 to 25 MHz, could be obtained with a 2 volt change in d.c. bias from 7 to 9 volts. Output power varied about 4.5 db over this range of bias voltage, but in practice this would not be a serious handicap because required frequency changes would be on the order of 1 or

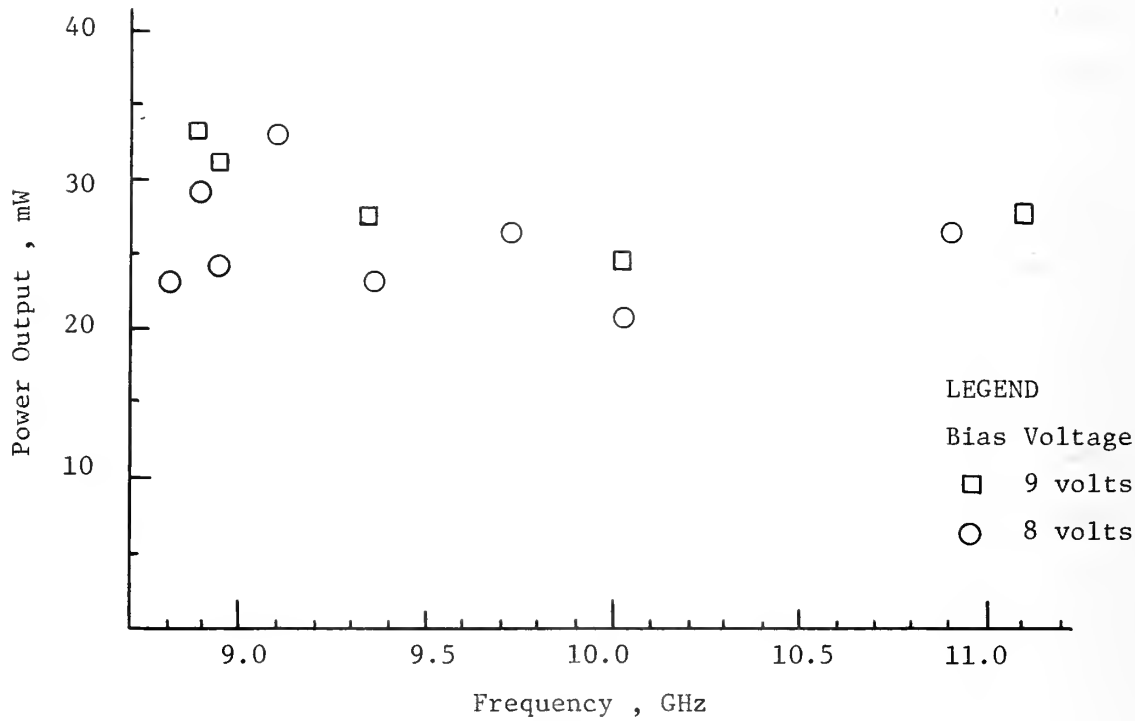

FIGURE 9.

MICROWAVE POWER OUTPUT , DIODE 7A

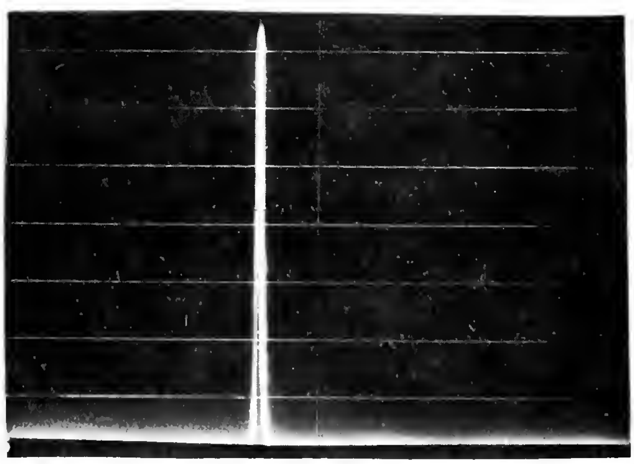

FIGURE 10. SPECTRUM OF GUNN-EFFECT OSCILLATOR AT 11.1 GHz

2 MHz to correct for temperature drift or similar factors. An operating point at 8.5 volts would allow plus or minus 5 MHz frequency change with output variations of less than one db. Figure (11) shows the variation of output power versus frequency deviation for voltage tuning at 9.9 GHz. Input voltage was varied one volt in each direction from an initial bias of 8 volts. This characteristic is typical of those obtained throughout the operating frequency range.

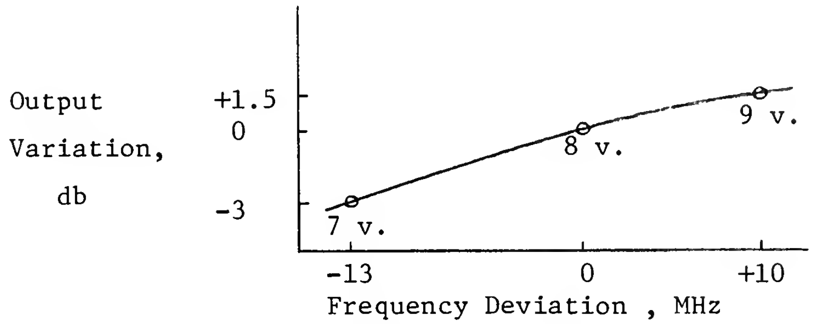

FIGURE 11. VOLTAGE TUNING CHARACTERISTICS

III. LOCKING TO UNMODULATED SIGNALS

LOCKING GAIN AND BANDWIDTH

Equation (9), rewritten here for convenience,

$$\eta = \frac{2\Delta_o}{\omega_o}\sqrt{\frac{P_o}{P_L}} \quad , \qquad (9)$$

predicts that for unmodulated locking signals the product of fractional bandwidth and the square root of power gain should be constant for given operating conditions. If the fractional bandwidth is plotted on a logarithmic scale versus power gain in db, data points should lie on a line of slope one decade per 20 db, with the intercept at 0 db gain equal to η, the locking figure of merit.

Measurements of locking gain and bandwidth were made at various frequencies in the range 8.8 to 10.0 GHz. The results of a representative set of these measurements are displayed in Figures (12) through (14). It can be seen that theoretical predictions are followed quite closely. The best performance recorded (Figure (13)) indicates that a bandwidth of 130 MHz is obtainable at 10 db gain, 40 MHz at 20 db gain, or 13 MHz at 30 db gain. These figures correspond to $\eta = 0.04$.

For gains over 25 db some data points lie considerably off the lines predicted by equation (9). This is due to the fact that for this magnitude of gain, reflections in the cavity input line can be of the same magnitude as the input. Thus, depending on the electrical length of the input line at the particular frequency in question, the reflections may add in or out of phase with the input signal, tending to either increase or decrease the net gain, or alternately, to increase or decrease the bandwidth obtainable at given input conditions.

Reflections in the input line were also responsible for hysteresis in the locking characteristics, which was occasionally observed. At some points more input power was required to lock to a signal than is predicted by equation (9), but once locked, less than the theoretical power was required to hold lock. This is due to the fact that once the oscillator is locked all reflections in the input line are at the locking frequency, whereas before locking reflections of the oscillator's output are at some other frequency.

Another effect noted was that of noisy or unstable locking signals. As seen in Figure (14), the locking figure of merit is

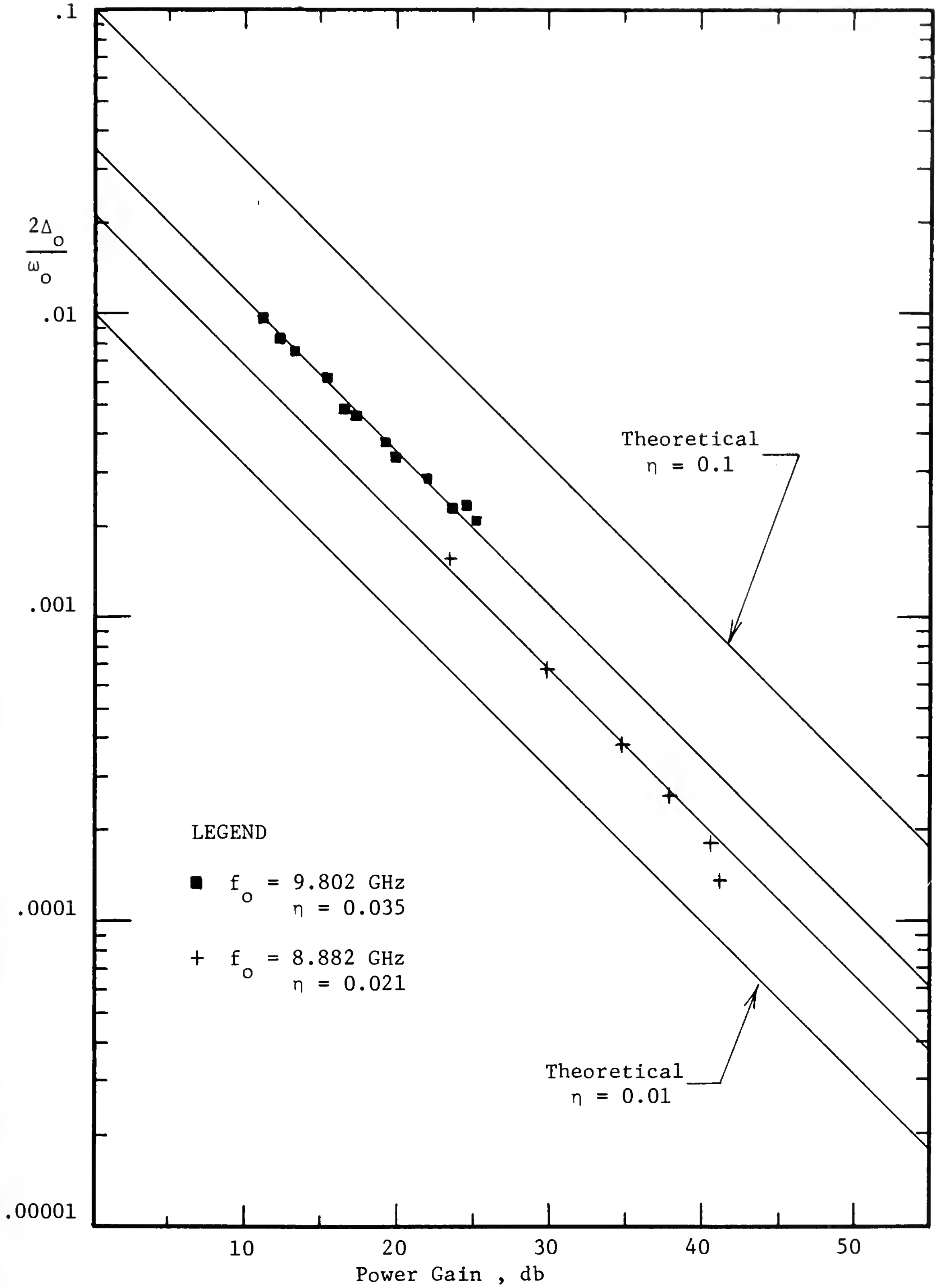

FIGURE 12.

CW LOCKING PERFORMANCE

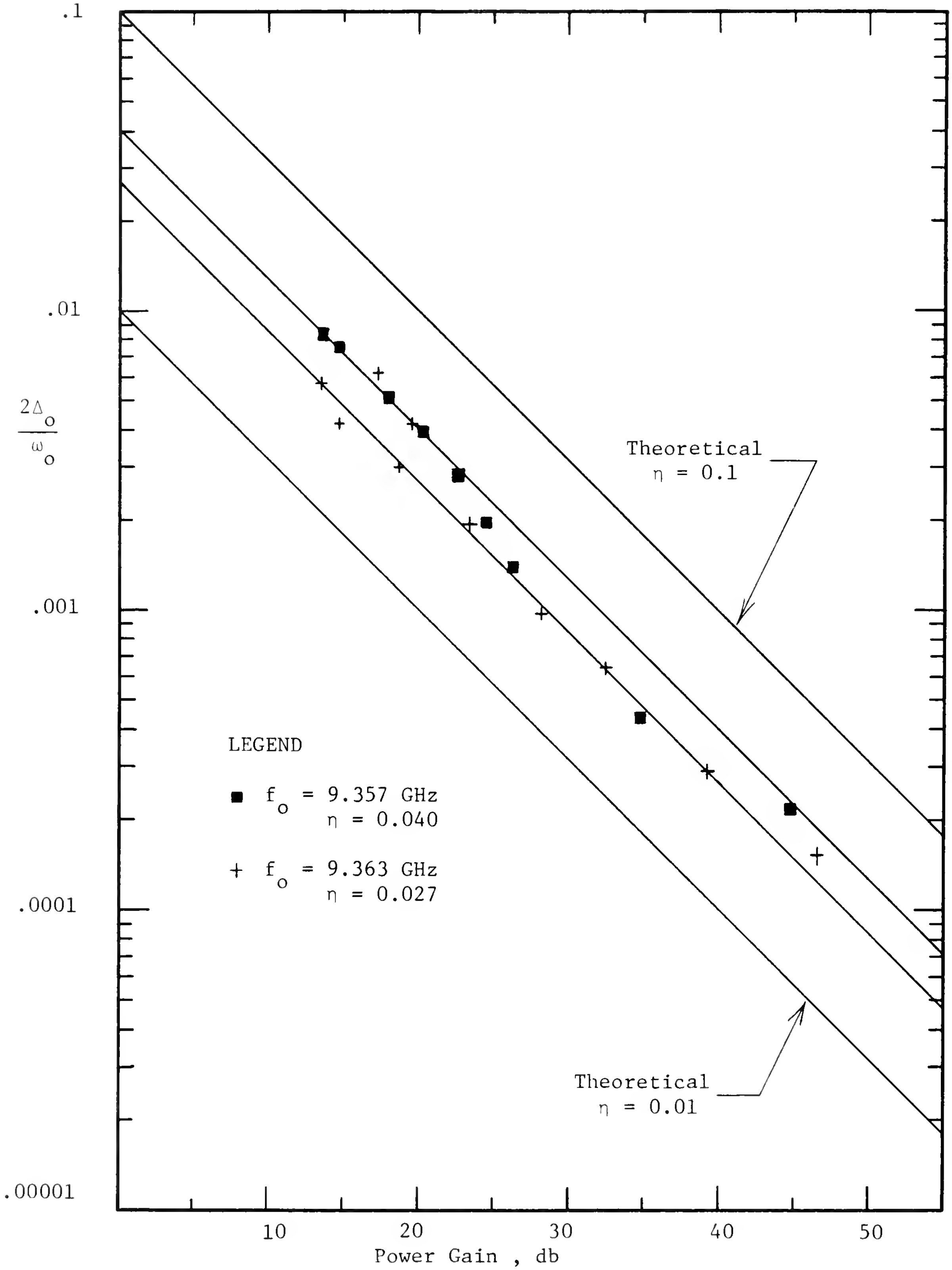

FIGURE 13.

CW LOCKING PERFORMANCE

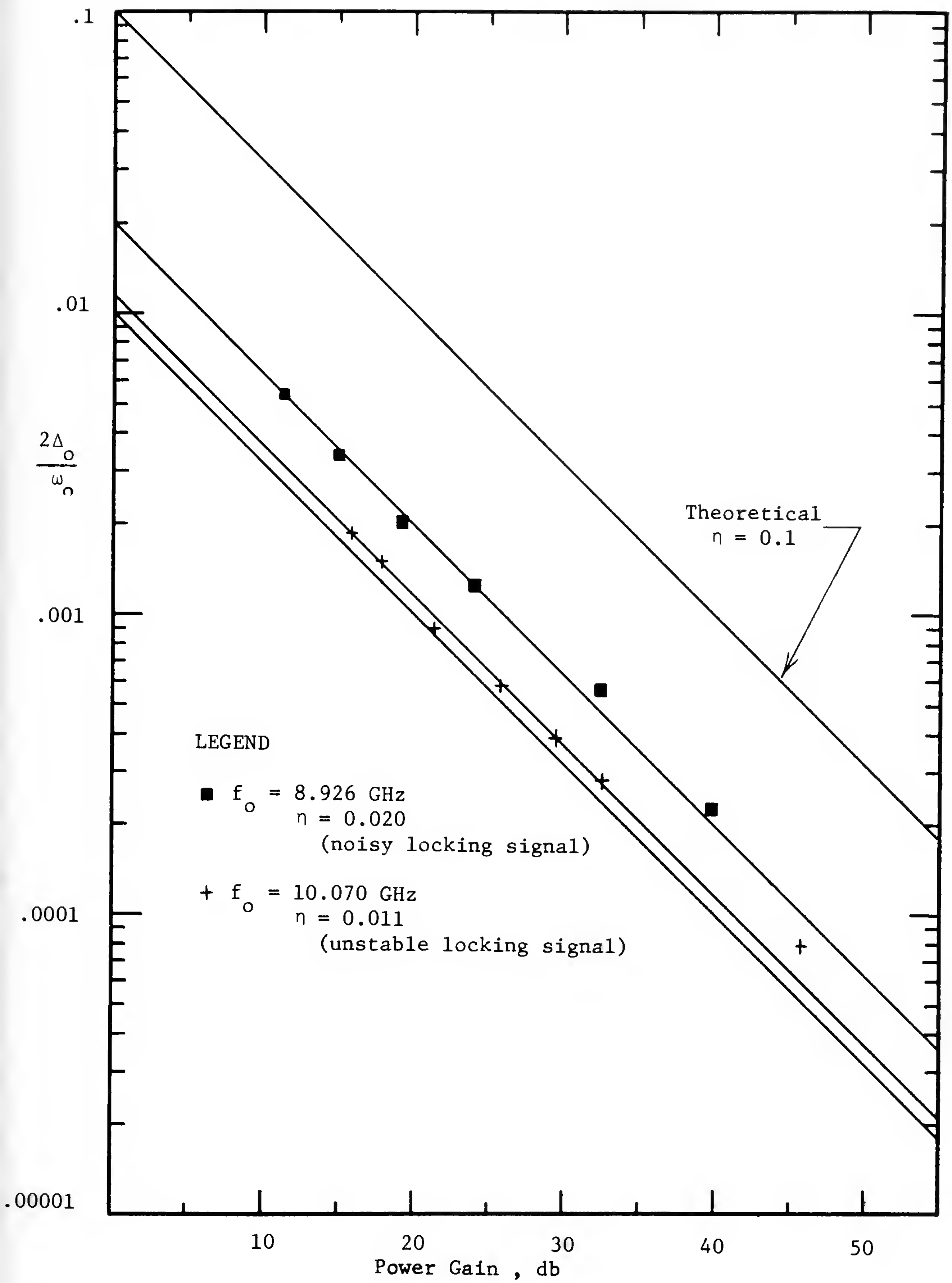

FIGURE 14.

CW LOCKING PERFORMANCE

reduced when the locking signal is noisy or unstable. It was found that locking gains were reduced 3 to 6 db by unstable signals, depending on the degree of instability. The instability appeared to reduce effects due to reflections, however, and the results of locking to these signals show fewer large deviations from the form of equation (9) than the results for more stable signals.

THE UNLOCKED DRIVEN OSCILLATOR

Figures (15) through (19) display the effect on an oscillator as the relative power of a perturbing signal is increased. Figure (15) shows the carrier at ω_o and the driver at ω_L with too little power to cause any frequency pulling. There is another first order sideband on the opposite side of the carrier which can be seen in Figures (16) and (17). Here the carrier frequency has shifted and the amplitude has been reduced. Note also that the first order sidebands are of unequal amplitude and that the driver is the only one which does not shift frequency. Figure (18) shows the situation just prior to locking. The first order sideband at ω_L is now larger than the carrier and higher order sidebands have appeared on the opposite side of the carrier. The carrier and all sidebands except the driver become increasingly unstable just before locking occurs. Figure (19) shows the locked spectrum -- a CW spectrum at the locking frequency.

Qualitative agreement with equation (18) was noted in the above series of photographs. It was therefore decided to investigate the quantitative aspects of the unlocked spectrum under more efficient locking conditions (higher η) than were present at the time the photographs in Figures (15) through (19) were made. Figure (20) shows the unlocked spectrum under conditions as follows: undisturbed frequency difference $2\pi\Delta\omega_o$ = 3 MHz, maximum gain for locking 29.1 db, and locking signal 30.1 db down from output. The vertical scale is logarithmic. Calculations based on the ratio of sidebands on the side of the spectrum opposite the driver to the carrier being $(2k)^n$, as in equation (18), gave k = 1.3. On this basis the locking range $2\pi\Delta_o$ is 2.3 MHz. Calculations based on the input amplitude yielded $2\pi\Delta_o$ = 2.6 MHz, in fair agreement with the value calculated from the unlocked spectrum.

IV. LOCKING TO FREQUENCY MODULATED SIGNALS

Experiments were conducted with frequency modulated locking signals at modulation frequencies ranging from 50 KHz to 10 MHz. Meaningful results were not obtained at frequencies above 1.5 MHz, however, because of excessive amplitude modulation on the BWO output.

As noted in Chapter II, when operating under ideal conditions the locked oscillator should not respond to amplitude variations of the input. When the input amplitude is varying, however, the effective locking power is the instantaneous power at the modulation minima. Thus for signals with significant amplitude modulation the effective locking power is considerably lower than the average power, necessitating an increase in locking signal amplitude if locking is to be maintained. If the degree of amplitude modulation is increased beyond a certain point the input necessary for locking will begin to violate the condition $E_L << E_o$ and amplitude modulation appears on the output.

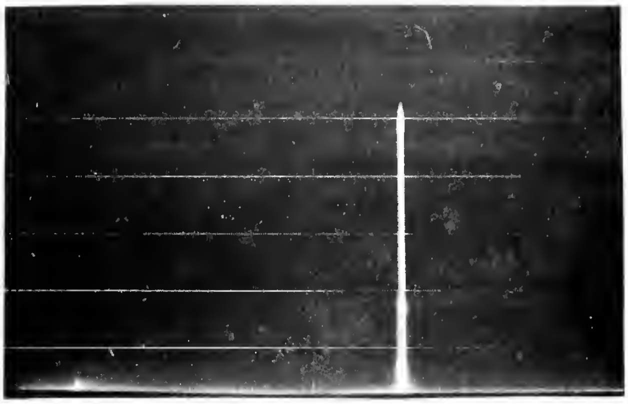

FIGURE 15. OSCILLATOR SPECTRUM WITH SIDEBAND AT DRIVER FREQUENCY

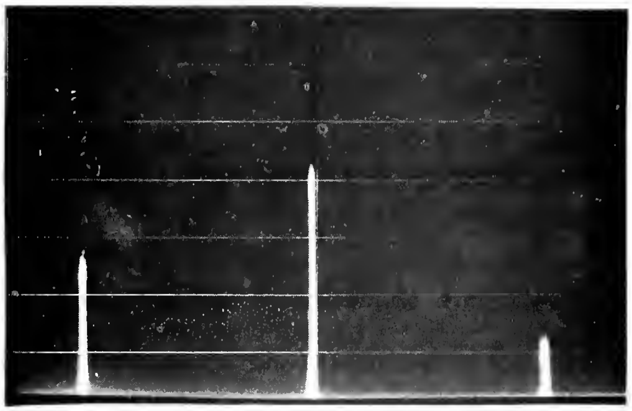

FIGURE 16. OSCILLATOR SPECTRUM WITH INCREASED DRIVER POWER, SHOWING UNEQUAL FIRST ORDER SIDEBANDS

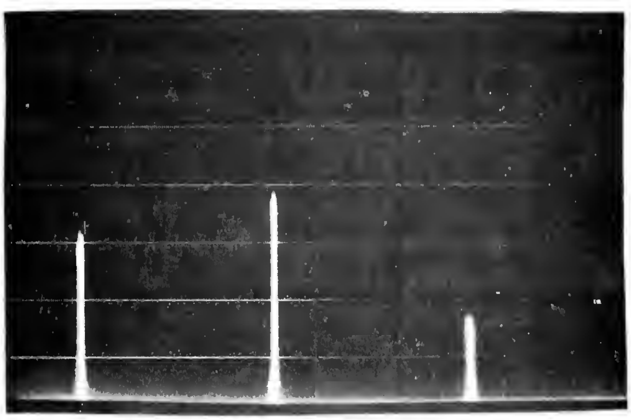

FIGURE 17. OSCILLATOR SPECTRUM WITH INCREASED DRIVER POWER. SECOND ORDER SIDEBAND OUTSIDE SPECTRUM ANALYZER RANGE

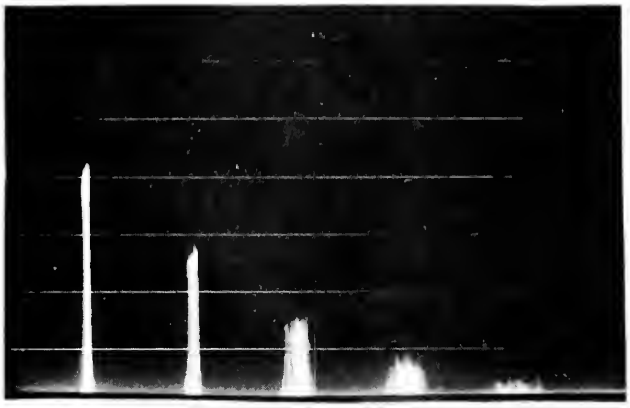

FIGURE 18. OSCILLATOR SPECTRUM
JUST PRIOR TO LOCKING

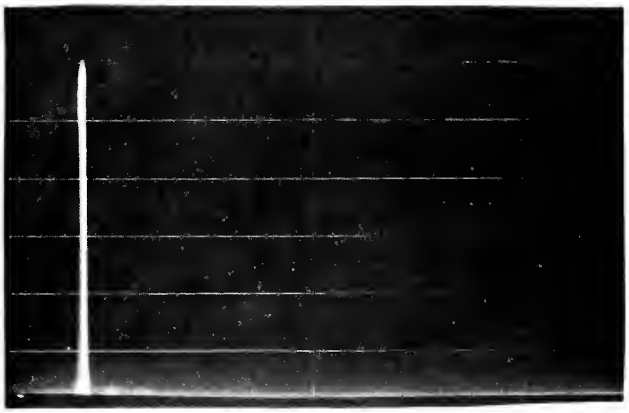

FIGURE 19. OSCILLATOR SPECTRUM
LOCKED TO DRIVER

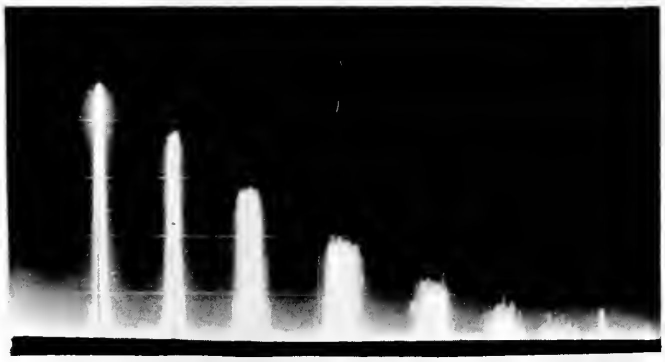

FIGURE 20. UNLOCKED DRIVEN
OSCILLATOR SPECTRUM
FOR $\eta \approx 0.02$

Some amplitude modulation was present on the BWO output for larger frequency deviations at all modulation frequencies used, but above 1.5 MHz the amount was such that the spectrum no longer resembled a pure frequency modulation spectrum, even for small deviations. This is demonstrated in Figures (21) and (22), which show the mixed AM-FM spectrum of the BWO output for two deviations at a modulating frequency of 5 MHz.

In the locking experiments it was found that if the amount of AM present on the input was not sufficient to cause serious deterioration of the input spectrum, such as that in Figures (21) and (22), the output was devoid of AM. When the input spectrum was mixed AM-FM, the output was also mixed AM-FM but the amount of AM was reduced.

Due to the poor modulation characteristics of the BWO, the locked oscillator's response to FM signals was not truly tested. For example, the gains recorded were influenced to a large degree by the amount of AM on the input. Similarly, the reduction in maximum modulation index with increasing modulation frequency was due primarily to the earlier onset of significant AM on the input rather than the characteristics of the locked oscillator at higher modulating frequencies.

Listed in Table II are the maximum frequency deviations and the corresponding approximate modulation indexes obtained at the listed modulation frequencies for gains of 30, 25, and 20 db. The maximum modulation index observed was approximately 20 for a modulating frequency of 0.5 MHz. The gain recorded for this measurement was 14.5 db.

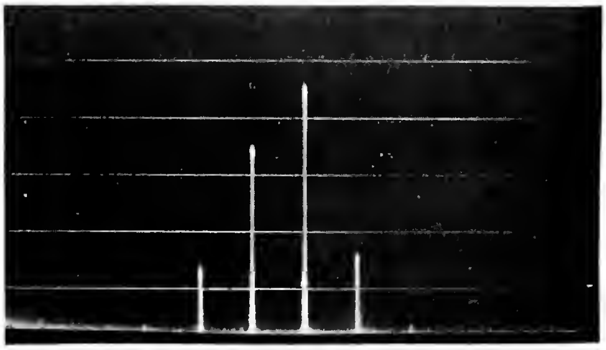

FIGURE 21. MIXED AM-FM SPECTRUM OF BACKWARD WAVE OSCILLATOR MODULATED AT f_m = 5MHz

FIGURE 22. MIXED AM-FM SPECTRUM OF BACKWARD WAVE OSCILLATOR MODULATED AT f_m = 5 MHz

TABLE II.
LOCKED OSCILLATOR FM PERFORMANCE

GAIN	30 db		25 db		20 db	
f_m	$\Delta f = \frac{BW}{2}$	m_f	$\Delta f = \frac{BW}{2}$	m_f	$\Delta f = \frac{BW}{2}$	m_f
0.1 MHz	0.8 MHz	5	1.2 MHz	8	1.6 MHz	11
0.5 MHz	2.5 MHz	3	3.5 MHz	4.5	5.5 MHz	8.5
1.0 MHz	4.0 MHz	3	5.0 MHz	3	-	-
1.5 MHz	9.0 MHz	3	7.5 MHz	3	-	-

Figures (23), (24), and (25) are photographs of the output spectrum for a modulation frequency of 0.5 MHz at 20 db gain. Figure (26) shows the spectrum of the input signal for approximately the same modulation index as Figure (25). Note that Figure (26) is not a pure FM spectrum.

All of the frequency modulation experiments above were performed with the free running frequency of the oscillator equal to the carrier frequency of the locking signal. Tests were also performed to determine the effect of offset between these frequencies. Table III gives the results for a modulation frequency of 0.5 MHz with modulation index $m_f \simeq 3$ (signal bandwidth 5 MHz). This corresponds to roughly the same conditions as the entry in Table II for f_m = 0.5 MHz at 30 db gain.

It appears that the additional input required when the signal carrier frequency is not equal to the free running frequency is roughly the same as that required to pull a CW signal over the same frequency deviation. No deterioration in the spectrum was discernable, although the noise performance probably was degraded somewhat, according to equation (24).

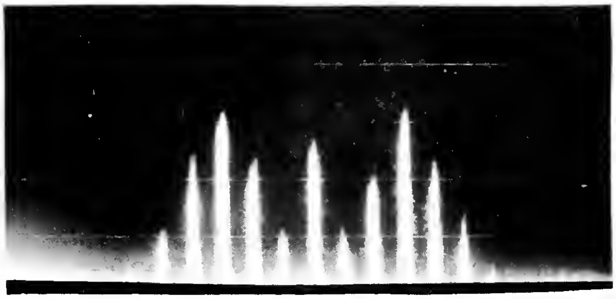

FIGURE 23. LOCKED OSCILLATOR SPECTRUM
FOR $f_m = 0.5$ MHz, $m_f \approx 4.5$

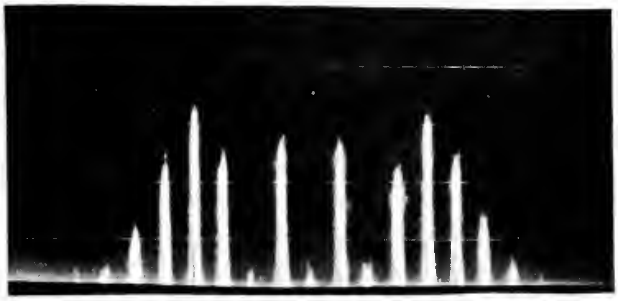

FIGURE 24. LOCKED OSCILLATOR SPECTRUM
FOR $f_m = 0.5$ MHz, $m_f \approx 5.3$

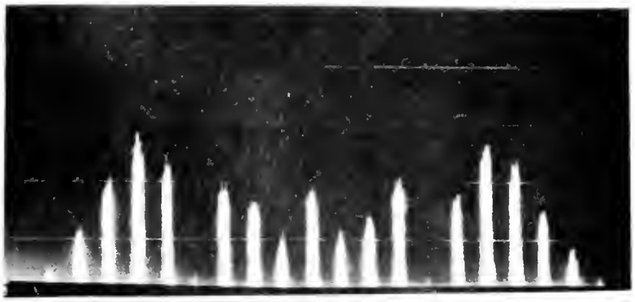

FIGURE 25. LOCKED OSCILLATOR SPECTRUM FOR $f_m = 0.5$ MHz, $m_f \approx 7.7$

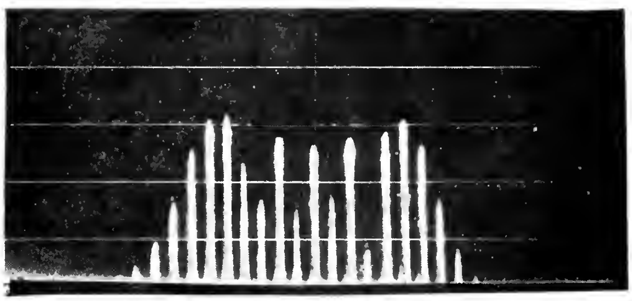

FIGURE 26. SPECTRUM OF INPUT, CONDITIONS APPROXIMATELY THE SAME AS FOR FIGURE 25

TABLE III.

LOCKED OSCILLATOR FM PERFORMANCE WITH OFFSET $(\Delta f)_o$ BETWEEN CARRIER AND FREE RUNNING FREQUENCIES

$(\Delta f)_o$	GAIN
0	30.6 db
0.5 MHz	28.6 db
2.0 MHz	28.1 db
3.0 MHz	25.2 db
4.5 MHz	21.9 db
8.0 MHz	18.9 db
12.0 MHz	18.1 db
14.0 MHz	17.2 db

f_m = 0.5 MHz, Signal BW = 5 MHz

The results above indicate that multiplexing several narrow band signals would be quite feasible. For example, three 4 MHz bandwidth signals with a 1 MHz guard band between adjacent signals could be amplified at 20 db gain. A reduction in the gain to 16 or 17 db would allow five of the same signals to be multiplexed.

In a multiplex signal situation, or with a single wideband signal, where nearly the entire locking range would be occupied by the signal bandwidth, it would be important to maintain the free running frequency equal to the center frequency of the information bandwidth. The voltage tunability of the Gunn diode would be useful for this purpose.

CHAPTER V

SUMMARY

The injection locked Gunn-effect oscillator was found to be an effective amplifier for frequency modulated microwave signals. Though the performance recorded is not considered to be optimum, it was sufficient to indicate the potential value of the locked Gunn-effect oscillator.

Due to the problems encountered in modulation of the locking signal source, the data taken on actual frequency modulation performance does not reflect the true gain and bandwidth obtainable. The results of the CW locking tests are more indicative of the gains and the bandwidths obtainable in amplification of good frequency modulated signals without excessive amplitude modulation. These figures indicate that amplification of 20 to 40 MHz bandwidth signals at 20 db gain could be achieved with the present equipment.

This conclusion is supported by the results of the tests of locking performance with frequency modulated signals with the carrier frequency not equal to the free running frequency. Since these tests were conducted with relatively small deviation signals, the effects of amplitude modulation were minimized. Thus the total bandwidth, including signal frequency deviation and the offset, gives a good estimate of the actual limits on FM performance.

Reduction of the loaded Q of the cavity from 25 to a value of 10 would result in an immediate increase in performance. This would amount to 8 db more power gain at a given bandwidth, or 2.5 times as much bandwidth at a given gain. The maximum modulation frequency, as given by equation (23), would also be increased by a factor of 2.5. If this reduction in Q could be achieved with a cavity suitable for incorporation in a miniaturized circuit no reduction in usefulness would result.

There are many potential applications for the locked Gunn-effect oscillator. One of the most interesting is as a non-demodulating repeater for low power microwave communications links. The device could be self-contained, consisting of a strip-line circuit with circulator and provision for mounting the cavity plus receiving and transmitting antennas. Input power could be provided by a battery incorporated within the assembly. The entire device would be of shoe box size, and could be left unattended for times up to the battery lifetime.

Another application would be as a preamplifier-limiter for a microwave receiver. This would offer 20 to 30 db of amplification plus limiting in a device completely compatible with an all solid state receiver.

It should be noted that in repeater or receiver applications the minimum detectable signal is a function of the locking parameters, including the output power of the oscillator. Thus to amplify very small signals, a low power oscillator, which nevertheless has a high locking figure of merit, is needed. If more output power were desired this oscillator could be cascaded with another of higher power. Since it may not be possible to make efficient Gunn diodes of very low output power, it might be necessary in some cases to use a tunnel diode oscillator as the first stage of such an arrangement to obtain the desired sensitivity.

The locked Gunn-effect oscillator could also be used in transmitter applications where high output power is not required. The voltage tunable magnetron has also been proposed[25] for this use in applications where 10 to 100 watts of output power are required, but the Gunn-effect oscillator's size, weight, and power supply advantages would make it more desirable for low power applications. Several oscillators could be operated in parallel, locked to the same input signal, to increase power output. Since 100 to 200 mW Gunn diodes are becoming available, output powers over one watt could be attained in this way.

Many interesting areas were not studied in the experimental work due to lack of time or adequate equipment. One of these areas is the upper limit on modulating frequency. Additionally, performance should be investigated in an actual data transmission system to determine noise and distortion characteristics, and to study the feasibility of operation with frequency multiplexed signals.

In the optimization of cavity design and other factors it would also be useful to construct a system using the same type of materials and techniques which would probably be used in production units. This would permit determination of the performance limits of practical systems.

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13. ABSTRACT

Although it has been known for many years that under the proper conditions an oscillator can lock to and follow an external signal of much smaller amplitude, this phenomena has not had widespread usage. The development of negative resistance solid state oscillator diodes, such as the Gunn diode, has brought about renewed interest in the locked oscillator, however.

The locking characteristics of an X-Band Gunn-effect oscillator have been investigated. The theory of injection locking is discussed and the experimental work performed is described. Amplifier performance of 20 db gain with 40 MHz bandwidth and 30 db gain with 13 MHz bandwidth is reported.

The advantages of the locked Gunn-effect oscillator as an amplifier for frequency modulated signals are its minimal power supply requirements, small size, low weight, and simplicity.

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